Medium Access for Underwater Acoustic Sensor Networks

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The underwater acoustic channel has many fundamentally different properties to the conventional radio-based wireless channel. Communication is changed drastically by acoustic propagation speeds that are five orders of magnitude slower than radio. This, coupled with bandwidth limitations, high transmit energy cost, complex multi-path effects, and high bit-error rates make the issue of medium access control (MAC) in an acoustic medium a challenging problem.

Recent work has begun to explore how multi-hop communication over short distances (500m or less) can reduce many of the channel complexities and improve energy efficiency (for example, see [1]), but multi-hop communication requires channel coordination. Our current work is therefore focused on understanding the challenges and potential solutions in MAC design for such short-range acoustic underwater sensor networks. Prior work on MAC for underwater acoustic networks has developed code distribution techniques with CDMA [6]. Recent work has extended radio-based sensor network MAC approaches to underwater for a specific class of applications [3]. More recent work has adapted CSMA techniques for underwater networks [2]. However we believe that the opportunities in underwater MACs have not been fully explored, particularly in low-cost, short-range networks.

In this abstract, we present a reservation based MAC protocol, called Tone Lohi (T-Lohi). (Lohi aptly means "slow" in Hawaiian.) The T-Lohi MAC introduces two novel ideas. The first is to detect *and* count the number of contenders during the reservation and use this information in building a traffic adaptive back-off algorithm. The slow propagation enables nodes to detect and count contenders, as long as the contention packets occupy the channel with a duration much less than the propagation delay.

The above ability is a major paradigm shift from the collision avoidance (CA) mechanism in terrestrial wireless networks. The collision detection removes the degradation of throughput at high loads (as we will show via simulation) while the contention count prevents the *packet starvation effect* in classical collision detection MAC's (*i.e.* Ethernet).

The second novel idea is to use a *wake-up tone* for *reserving* the data transmission. The wake-up tone detector, a hardware optimization being developed on our acoustic modem [5], allows nodes to listen to the tone with minimal energy consumption. Using the wake-up tone provides substantial energy savings during the reservation phase. The reservation ensures that there is no collision during the following data transmission, avoiding energy waste.

1 The Tone Lohi MAC Protocol

The T-Lohi protocol consists of a reservation period (typically on the order of tenths of a second and consisting of multiple contention slots), followed by a reserved data period. Nodes transmit a tone during the reservation period if they intend to reserve the data period. Nodes hearing a tone during the reservation period will back off. A node "wins" a data slot reservation if it transmits and does not hear another tone within a contention slot. There are two variants to the T-Lohi protocol: synchronized tone (ST) and unsynchronized tone (UT) Lohi protocols. For the purpose of this poster and brevity we describe only ST-Lohi as it is more efficient protocol, provided synchronization can be maintained. (Prior work suggests this is feasible [4].)

In ST-Lohi, all nodes in the network are aligned to contention slots that are equal to the maximum propagation delay plus the tone length. All contending nodes are forced to send their reservation tones at the beginning of these slots, if they are not restricted by back-off. After sending the tone, a node waits and listens to possible arrival tones for the rest of the contention slot. If it does not hear another tone, it wins the reservation, and immediately transmits its data (Figure 1). Otherwise, it is the case that multiple nodes try to reserve the medium, and they should back-off and retry. Nodes can count the number of contenders in a given slot by counting the number of received tones, and use this number as their back-off window size. At the end of data transmission, nodes that attempted contention in the previous reservation period do so with a smaller window than the nodes that did not contend at all. This helps minimize the packet delay by prioritizing nodes that have already contended.

An interesting observation of medium access in the *high-*

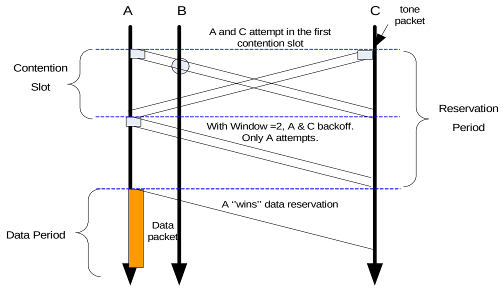

Figure 1. The ST-Lohi MAC

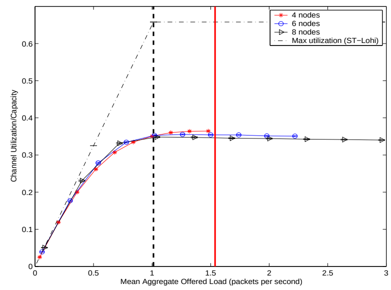

Figure 2. Channel utilization as mean aggregate load varies, at different densities.

latency acoustic medium is what we call *space-time uncertainty.* In this medium, not only concurrent transmissions can cause collision, but transmissions at different time and distances can also cause collision. Synchronizing the transmit time removes one dimension of uncertainty (time), and waiting for the maximum propagation delay removes the second (space). This uncertainty is why ST-Lohi waits the maximum propagation time to guarantee any possible collisions have been detected. If no other contention tones are sent, the contending node has reserved the channel and can start transmitting in the next slot. This space-time separation also allows us to *count* the number of contenders, since even though they transmit at the same time, they are usually at different physical places in space, thus their contention tones arrive at different times. We use this count to intelligently select the backoff for subsequent contention periods.

We achieve energy efficiency by using the wake-up tone abstraction that allows node to send and receive tones without having to stay fully active for the entire contention slot. Note that our current design only considers fully connected networks. We are working on extending it with an efficient multi-hop scheme that utilizes specific features of the acoustic medium to avoid common multi-hop issues.

2 Experimental Results

To evaluate ST-Lohi we extended our time synchronization simulator (from [4]) to support packet-level MAC protocols. Here we report preliminary simulation results with different node density in a 300x400m area. Each node generates traffic with a Poisson arrival rate. Each packet is 650 bytes long, and we assume modem bandwidth of 8kb/s. Each datapoint represents the mean value of 1000 experiments. Error bars indicate 95% confidence intervals.

Figure 2 shows channel utilization as a function of aggregate offered load for three different network densities. It also shows two theoretical targets: The solid vertical line shows the maximum accepted load that could be achieved with an omniscient MAC. The dotted vertical line shows the best practical accepted load achieved by ST-Lohi assuming there was never contention. A dotted line is also shown to show the best capacity achieved by ST-Lohi for varying load. As packet transmission time is twice the required contention time the best practical capacity of ST-Lohi is two-thirds the channel capacity. (This value could be changed with different packet sizes or modem range and bandwidth.)

We see three observations in this simulation. First, it is very efficient at low offered loads. For aggregate offered load less than 0.5 packets/s, ST-Lohi is very close to maximum practical capacity. We therefore conclude that ST-Lohi is efficient at low contention rates.

Second, as offered load approaches the practical capacity (0.5–1 packet/s), we see ST-Lohi reaches 50% of maximum practical capacity. This decrease is due to greater contention, since nodes now require more than one contention slot to determine which single node has acquired the channel.

Finally, as offered load exceeds practical capacity (more than 1 packet/s), we observe that ST-Lohi performance is stable. This means that MAC performance does not degrade at higher load, but instead maintains a steady capacity. Furthermore, comparing evaluation for different densities shows that ST-Lohi is stable, independent of the node density. The reason for this load independent capacity is collision detection capability inherent to medium access in Lohi MAC. Thus, even under heavy load, the average contention slots until a data period is reserved remains constant. We conclude that ST-Lohi efficiency does not degrade with offered load or density.

3 References

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Medium Access for Underwater Acoustic Networks

(Work in progress)

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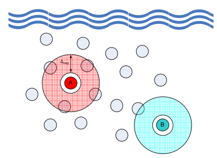
GOALS:

- Identify the challenges of medium access in underwater acoustic networks (UWSN)
- Develop protocols to deal with such challenges
- Initial evaluation of the performance of these protocols

Challenges of Medium Access in UWSN

Challenges

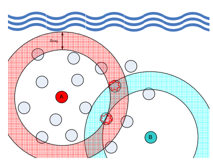
- Low bandwidth, high BER, large multipath fading
- High *transmit energy cost*
- Large propagation latency (RTT in the order of 700 ms)



Both A and B transmit after CCA

Implications

- Complex physical layer/modem design
- Tight bandwidth and energy constraints
- Medium access has **space time uncertainty:**
  - Collision not only because of transmission at specific instants
  - but also due to relative location of transmitter



...but collision still occurs with a high probability!

Our Approach

- Short range (<500m) over multi-hops reduce phy complexity.
- Exploit ultra low power wake-up hardware for energy conservation
- Design a MAC protocol to minimize the impact of propagation latency

Initial Evaluation

Methodology

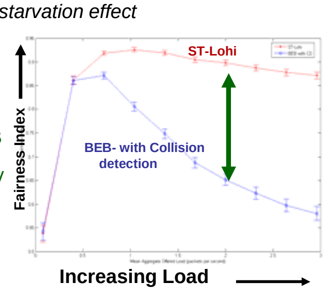
- First perform simulations in a custom built simulator
  - Later in air test bed deployment with acoustic modem
  - Protocol dynamics under varying load with Poisson traffic
  - 650 byte packets @ 8Kbps, 500m fully connected topology

Channel utilization

- Three observations (due to collision detection capability) :
  - Efficient at low load (less than 0.5 pkts/sec)
  - Utilization converges to 33% as load equals capacity
    - Less than optimal due to longer reservation period
  - Stable and load independent beyond channel capacity

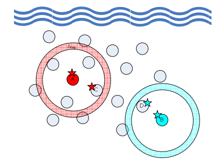
Fairness

- Results show that a simple binary exponential back-off (BEB) algorithm gives similar throughput
  - only if collision detection is assumed (as in Ethernet)
- Still suffer from unfairness i.e. *packet starvation effect*
- Jain's Fairness index: $\frac{(\sum x)^2}{n \times \sum x^2}$
- x= data packets sent
- ST-Lohi is significantly fairer than BEB
  - knows contention level due to ability to count contenders
  - Hence decides on a fairer back-off



Tone-Lohi (T-Lohi) Protocol

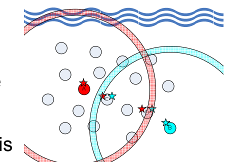
- **Lohi** stands for "*slow*" in Hawaiian
  - From the slow propagation speed of acoustic medium!



Short tones allows collision detection

Preliminary Design

- Alternating reservation and data periods
- Data period reserved by:
  - transmitting **short** tones and…
  - listening for maximum propagation time (330 ms) i.e. contention period (CP)
  - Successful reservation iff a single tone is sent in a CP
  - Back-off when other tones detected.



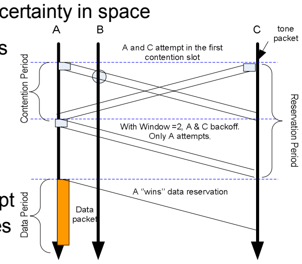
..and contender count

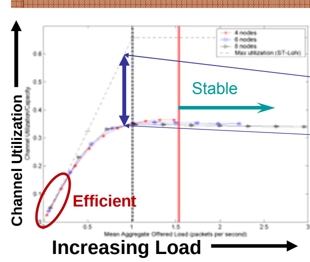
Novel Ideas

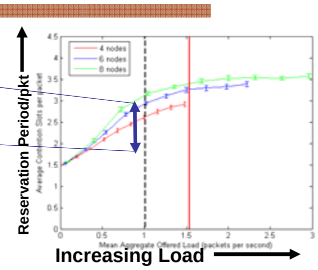
- Exploit hardware wake up using short (<5ms) tones:
  - Little energy cost of listening over long periods
  - Short duration; thus low local collision probability
- **Detect** and **count** other contenders (if they exist)
  - Collision detection (CD, like Ethernet) leads to good utilization, independent of load
  - Use *contender* count to adapt back-off to traffic, improving fairness

Synchronized T-Lohi (ST-Lohi)

- Synchronized CPs, and tone sent only at beginning
  - Synchronization removes uncertainty in time
  - Waiting the entire CP removes uncertainty in space
- If contention detected in a CP, nodes back off:
  - Nodes that loose will have higher priority to transmit in the next reservation period.
- After data period ends, nodes attempt reservation based on traffic estimates from previous reservation period.







Conclusions

- Identified key challenges of acoustic medium access
- Preliminary design of a reservation MAC using low power wake up tone for energy savings.
- Contention detection and counting gives efficient channel utilization with fair channel access.
- Future Work:
  - Multi-hop extensions and handling hidden terminal
  - Refining the protocol, identifying protocol issues, and comparing with existing MAC part of future work

For more information and code: http://www.isi.edu/ilense/snuse

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